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Advancements in Piezoelectric Materials for Biomedical Applications: A Review

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ABSTRACT
Piezoelectric materials have the unique ability to convert mechanical energy into electrical energy and vice versa, allowing them to both generate electricity under stress and deform in response to electrical stimulation. This dual functionality makes them a highly promising candidate in biomedical engineering. Over the past few decades, researchers have explored their potential for applications such as tissue engineering, artificial muscles, biomedical implants, and bone tissue regeneration. The growing demand for self-powered and biocompatible devices has increased interest in these materials as they can operate without external power sources by harvesting energy from natural body functions. However, a major research gap remains in developing biodegradable and non-toxic piezoelectric materials that integrate safely into living tissues while maintaining sufficient mechanical strength and electrical responsiveness. Many studies have focused on electrical performance, with less emphasis on long-term biocompatibility and degradation in biological environments. This review analyses the properties and biomedical applications of piezoelectric materials, specifically their biocompatibility, biodegradability, and electromechanical characteristics in skin and neural regeneration, artificial muscles, pacemaker and cochlear implants, and bone tissue regeneration. Future research should prioritize non-cytotoxic, biodegradable composites that balance biocompatibility and performance. Advancements in this area could revolutionize biomedical devices by enabling self-powered, responsive healthcare solutions.
Keywords: Piezoelectric, Tissue Regeneration, Artificial Muscles, Biomedical Implants

1 INTRODUCTION

In the field of biomedical engineering the development of advanced biomedical materials is crucial for the improvement of medical implants, prosthetics, and devices. These materials must be able to function both for mechanical and electrical functions but also simultaneously interact safely with the human body. Biocompatibility describes the ability of a material to perform with an appropriate host and ultimately governs the success of any biomedical device (Williams, 2023). This required necessity has driven intense research into smart materials that can dynamically respond to physiological stimuli thereby enabling therapeutic and diagnostic systems.

An emerging smart material in the field of biomedical devices are piezoelectric materials. They uniquely convert mechanical energy into electrical energy (and vice versa) and this electromechanical coupling means that piezoelectric materials can act as transducers generating electric signals from bodily movements or providing mechanical actuation under an applied voltage (Zaszczyńska et al., 2024). These unique characteristics are highly relevant in biomedical applications, for example, piezoelectric elements can harvest biomechanical energy to power implants or can deliver electrical stimulation to tissues without any external power source (Zaszczyńska et al., 2024). The development of devices capable of interacting with biological systems in a dynamic and intelligent way has recently gained significant momentum. As a result, these materials have been explored for a wide range of innovative applications including tissue regeneration, artificial muscles, biomedical implants, and bone tissue regeneration. By converting natural body motions into bioelectric signals, piezoelectric biomaterials allow for dynamic interaction with biological systems in ways that conventional passive materials cannot. Piezoelectric materials used in biomedical devices span inorganic ceramics, organic polymers, and organic–inorganic composites, and each category offers distinct advantages and challenges (Zaszczyńska et al., 2024). Inorganic piezoelectric ceramics (such as lead zirconate titanate, PZT, or barium titanate) generally exhibit strong piezoelectric coefficients, making them highly sensitive and effective for signal transduction. Organic piezoelectric polymers (notably polyvinylidene fluoride, PVDF, and its copolymers) offer flexibility and better inherent biocompatibility. Composite approaches combine ceramics with polymers to tune properties and improve overall performance. The ceramic lead zirconate titanate (PZT) and the polyvinylidene

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fluoride (PVDF) are frequently highlighted in this literature review for their adaptability and proven effectiveness in biomedical environments (Shi & Yeatman, 2021).

Current challenges and research gaps in piezoelectric biomedical applications center on material safety and long-term performance. A foremost concern is ensuring biocompatibility and non-toxicity. Any piezoelectric material intended for implantation must not leach harmful ions or degradation products into surrounding tissues. PZT devices can deliver strong electromechanical responses but contain lead, a toxic element, whereas PVDF based devices are lead-free and more biocompatible (Xu et al., 2024). PVDF is noted for its flexibility and has been used in implantable sensors and energy harvesters due to its safe integration with tissue (Xu et al., 2024). However, each presents different negative aspects: PZT ceramics tend to be brittle and may pose toxicity concerns while polymers like PVDF, despite being biocompatible, have lower piezoelectric output and are usually non-degradable (potentially persisting as foreign bodies).

A key challenge in the biomedical application of piezoelectric materials is achieving a balance between degradation and long-term stability. Temporary devices such as tissue scaffolds benefit from biodegradable piezoelectric materials that can safely resorb which eliminates the need for surgical removal. Comparatively, permanent implants must resist fatigue and maintain function in physiological environments (Xu et al., 2024). Manufacturing complexities of piezoelectric material also exist as there is the need for precise dipole alignment (poling), electrode integration, and the maintenance of mechanical integrity in moist biological conditions, all of which complicate the production of implantable piezoelectric devices like nanofiber scaffolds or flexible sensors (Zaszczyńska et al., 2024). Current research is focused on developing biocompatible and biodegradable piezoelectric systems, such as poly-L-lactic acid (PLLA) and naturally derived piezoelectric biomolecules which avoid toxic elements and reduce long-term implantation risks (Wu et al., 2024). Future piezoelectric biomaterials must strike a balance between electromechanical performance, biocompatibility, and degradability, ensuring they fulfill their functional role and then either remain inert or degrade safely within the body (Zaszczyńska et al., 2024).

The aim of this literature review is to provide a comprehensive overview of piezoelectric materials in the biomedical field and how they can be safely and effectively integrated into healthcare. We classify piezoelectric materials into their organic, inorganic, and composite categories and analyze their key mechanical, electrical, and biological properties relevant to biomedical use. We then examine their applications in biomedical engineering focusing on areas such as tissue regeneration, artificial muscles, biomedical implants, and bone tissue regeneration, to illustrate the capabilities and impact of piezoelectric systems. We highlight the current challenges (material degradation, cytotoxicity, manufacturing complexity) that must be addressed to translate these technologies into clinical practice. Finally, the review highlights future research directions aimed at optimizing piezoelectric materials which emphasise the need to achieve an optimal balance of biodegradability, biocompatibility, and mechanical strength. This balance is essential to fully optimizing piezoelectric devices as seamless, integrated, and life-enhancing technologies within the human body.

2 PIEZOELECTRICITY: AN OVERVIEW

Piezoelectricity, also known as the piezoelectric effect, is a property of several insulating, dielectric materials (Kamel, 2022). A piezoelectric material is able to produce an electric charge in response to mechanical deformation, known as the direct piezoelectric effect (Kamel, 2022). They are also capable of performing the reverse operation, producing mechanical deformation in response to the generation of an electric field, known as the converse piezoelectric effect (Kamel, 2022). These two effects are displayed in **Figure 1**.

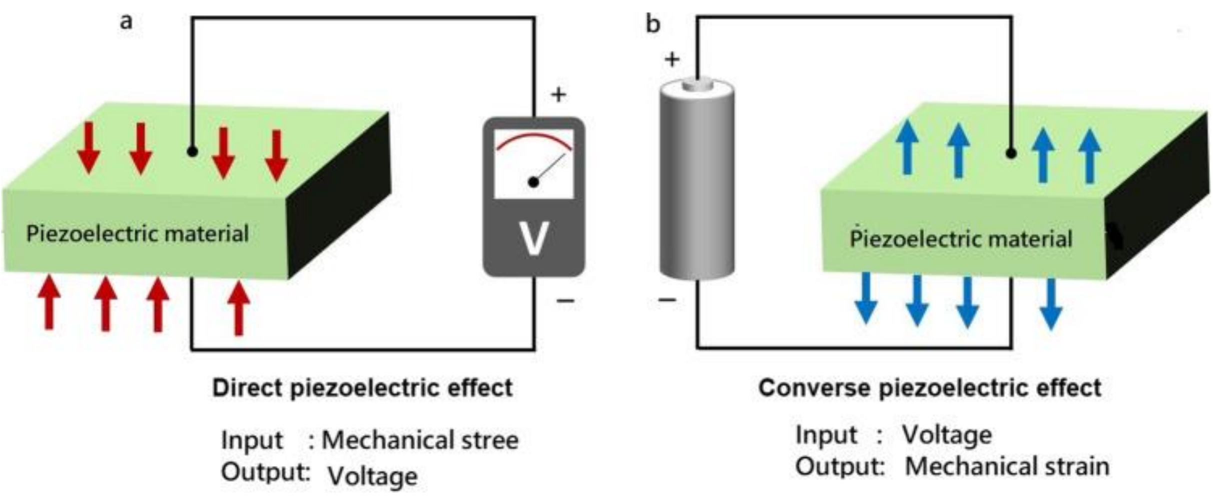

Figure 1: Schematic Displaying the Two Piezoelectric Effects (Kamel, 2022)

In terms of the piezoelectric effect, piezoelectric materials generate an electric dipole in response to an applied force (Kamel, 2022). As such, piezoelectric properties are found in materials with non-centrosymmetric structural arrangements as the lack of symmetry allows a dipole to easily form (Kamel, 2022). Through the application of external mechanical stress, deformation of the piezoelectric material's structural arrangement can occur (Kamel, 2022). This separates the positive and negative centres of molecules in the structure, producing a net dipole as fixed, opposite charges are redistributed on opposite surfaces within the molecule (Kamel, 2022).

Mathematically, piezoelectricity is a linear proportional relationship between electrical and mechanical states, determined by the piezoelectric coefficient, d (Kamel, 2022). The piezoelectric coefficient describes the amount of charge that is generated per unit of applied force when working with the direct piezoelectric effect (Kamel, 2022). For the converse piezoelectric effect, d represents the deflection produced per unit of applied voltage (Kamel, 2022). Materials with higher piezoelectric coefficients are desirable—especially for devices designed to be sensitive to small changes in the environment—as it implies that the material can efficiently convert mechanical energy to electrical energy and/or vice versa. In addition, as the piezoelectric coefficient is inherently a tensor value, it is typically written using subscripts x and y (d_{xy}) to respectively describe the directions of the electric field and stress/strain (Kamel, 2022). Common piezoelectric coefficient directions include the longitudinal (d_{33}), transverse (d_{31}) and tangential (d_{15}) directions (Kamel, 2022).

3. PIEZOELECTRIC MATERIALS IN TISSUE REGENERATION AND TISSUE ENGINEERING

Traditional medical interventions in the forms of surgery and medication are limited in their ability to repair and reconstruct damaged tissues and organs due to accidents, aging and illness (Wu et al., 2024). Many tissues in the human body exhibit piezoelectric properties, which have made the application of piezoelectric materials as electrically active biomaterials more prominent (Wu et al., 2024). Electric signals are critical to tissue regeneration processes and the regulation of cellular behaviour. So, piezoelectric materials that can spontaneously generate these signals have been examined as a potential means of promoting and enhancing the differentiation and proliferation of cells for the repair of tissue (Wu et al., 2024).

3.1 Classifications of Piezoelectric Materials

Piezoelectric materials employed in tissue engineering can be systematically categorized based on their composition and origin, with each class presenting distinct advantages and limitations that determine their sustainability for specific biomedical applications (Wu et al., 2024). Piezoelectric materials can be grouped into the following three different classes based on their composition (Wu et al., 2024).

3.1.1 Inorganic Piezoelectric Materials

Inorganic piezoelectric materials consist of crystalline and ceramic substances that demonstrate strong piezoelectric responses, characterized by their highly ordered atomic structures that enable efficient electromechanical coupling (Kamel, 2022). Piezoelectric crystals refer to materials in which their constituents (atoms, ions, molecules) are highly ordered and geometrically arranged into a three-dimensional lattice (Kamel, 2022). Perfect crystals that have a regular, consistent crystallographic arrangement have consistent and more stable piezoelectric effects (Kamel, 2022). This would include compounds such as SiO_2 and $LiTaO_3$ (Kamel, 2022). In contrast, polycrystals with less consistent structure such as $BaTiO_3$ and $PbTiO_3$ have more varied piezoelectric effects (Kamel, 2022). As a result, artificially created regular crystals are used over their naturally occurring components in piezoelectric devices (Kamel, 2022).

Piezoelectric ceramics are polycrystalline materials that are neither metallic nor organic. Individual grains in a ceramic spontaneously form a localized region of polarization in the same direction resulting in a significantly higher piezoelectric coefficient compared to regular crystals (Wu et al., 2024). Barium titanate, $BaTiO_3$, was the earliest widely used piezoelectric ceramic due to its high piezoelectric coefficient, low cost and simple preparation (Wu et al., 2024). $BaTiO_3$ nanoparticles were found to—in response to pH changes—invade the cells of tumors, inducing mechanical damage and facilitating their removal (Wu et al., 2024).

However, many highly piezoelectric ceramics exhibit cytotoxic behaviour. The cytotoxicity of piezoelectric ceramics can be reduced by altering their composition or dosage for use in tissue engineering (Wu et al., 2024). For example, lead zirconate titanate (PZT) has a significantly high piezoelectric coefficient but there is concern surrounding its use in tissue engineering due to a potential toxic exposure to lead (Kamel, 2022). As a result, piezoelectric ceramics have been developed using less cytotoxic elements such as lithium sodium potassium niobate (LNKN) and potassium sodium niobate (KNN) (Kamel, 2022). Additionally, $BaTiO_3$ is also cytotoxic, with its cytotoxicity potentially reduced by depositing either hydroxyapatite (HA) or collagen— both bioactive materials—onto its surface and increasing its binding ability to bone (Wu et al., 2024).

3.1.2 Organic Piezoelectric Materials

These materials refer to piezoelectric polymers, which can either be natural or synthetic macromolecules (Kamel, 2022). Unlike piezoelectric ceramics, piezoelectric polymers have relatively low piezoelectric coefficients (Wu et al., 2024). However, this is rectified by their higher flexibility and lower stiffness in comparison, making them more compatible with the regeneration of soft tissues (Wu et al., 2024). Most piezoelectric polymers are biocompatible and in general, are not cytotoxic, making them promising candidates for medical device production (Kamel, 2022).

Synthetic piezoelectric polymers are created within processing conditions that allow their electromechanical efficiency and optical transparency to be optimized (Kamel, 2022). They are also seen as desirable biomaterials due to their ease of manufacturing (Kamel, 2022). Two of the most widely used piezopolymers are polyvinylidene fluoride (PVDF) and Poly-L-lactic acid (PLLA). PVDF has a high piezoelectric coefficient and good mechanical strength, being extensively studied as a result. PLLA is a biocompatible, biodegradable and bioresorbable thermoplastic that has been approved for use in medical implants by the United States Food and Drug Administration (FDA) (Wu et al., 2024). Natural piezopolymers are found naturally in the human body and within other living organisms. They have low cytotoxicity and are biodegradable, resulting in their wide use in tissue engineering (Wu et al., 2024). These include two of the four major classes of biological macromolecules; polysaccharides and proteins.

Polysaccharides are carbohydrates composed of many monosaccharide (sugar) molecules bonded together by glycosidic linkages. Polysaccharides such as cellulose (found in plant cell walls) and chitosan (found in the exoskeletons of shellfish) have become a point of interest in piezoelectric energy harvesting due to the demand for eco-friendly materials (Wu et al., 2024). This is due to their abundance, renewability, sustainability and relatively low costs (Wu et al., 2024). Cellulose is linear, composed of glucose monomers, and has a high degree of structural order or crystallinity. The large number of polar-covalent hydroxyl groups in cellulose allow asymmetric dipoles to form with ease—producing piezoelectric activity (Wu et al., 2024). Chitosan also exhibits similar piezoelectric properties to cellulose because of its non-centrosymmetric crystal structure and is commonly used in the application of sensors (Wu et al., 2024).

Proteins are large macromolecules composed of large chains of amino acid monomers bonded together by peptide bonds. Amino acid structure consists of a central carbon atom, a carboxyl group (—COOH), an amino group (—NH_2) and a variable side chain (R group) that determines each amino acid's polarity and distinguishes them from one another (Wu et al., 2024). R groups also result in different crystal structures for different amino acids—in turn determining their piezoelectric properties (Wu et al., 2024). These side chains also influence how intramolecular electric dipoles interact and are arranged (Wu et al., 2024). Glycine, the only amino acid that displays achirality, has been considered as a possible material for piezoelectric sensors and energy harvesting due to its allotropy. Glycine has three distinct phases, the α, β and γ phases. The β and γ phases of glycine have a non-centrosymmetric structure and as a result display significant piezoelectric properties (Wu et al., 2024). Other amino acids exhibit piezoelectricity due to their chiral structural symmetry, such as DL-alanine, L-leucine, L-tyrosine, and isoleucine (Wu et al., 2024).

In terms of piezoelectric proteins themselves, their different sequences of amino acids have allowed certain proteins to exhibit piezoelectric properties (Wu et al., 2024). An example of a piezoelectric protein is collagen. When subjected to tensile or torsional loading, tiny separations of charge are produced in its long triple helix chains, resulting in piezoelectric effects (Wu et al., 2024). The use of collagen in sensor applications is currently being explored, however it has relatively weak piezoelectric properties. Silk fibroin (SF) is another example, which is the main structural component of silkworm cocoons. SF has both great mechanical properties and piezoelectric properties making them a preferred material for biodegradable piezoelectric nanogenerators (Wu et al., 2024)—devices that convert mechanical energy into electrical energy. These nanogenerators can function as pressure sensors for the medical monitoring of signals of physiological origin (Wu et al., 2024). SF is also both biodegradable and biocompatible, holding value in regenerative medicine (Wu et al., 2024). This is due to its capability to promote wound healing by stimulating cell growth, increasing cell proliferation and assisting in the migration of various cell types involved in the tissue repair process (Vidya & Rajagopal, 2021). An additional example is elastin, an extracellular matrix (ECM) protein that is mainly found in connective tissues. Elastin provides tissues of the integument, blood vessels and lungs with elasticity and flexibility (Wu et al., 2024). Under mechanical stress, elastin is able to produce a piezoelectric charge that possibly plays a role in the regulation of vascular smooth muscle cell proliferation and migration and in blood vessel repair (Wu et al., 2024). Furthermore, elastin's piezoelectric properties may also be involved in the binding of oxygen to heme groups within hemoglobin as well as regulating pressure within blood vessels (Wu et al., 2024). Piezoelectric proteins are only weakly piezoelectric though, however, this can be rectified through procedural modifications or the combination of materials to increase piezoelectric properties (Wu et al., 2024).

3.1.3 Piezocomposites

In order to rectify the low piezoelectric properties of piezopolymers, piezocomposites can be formed by combining piezoelectric polymers and ceramics to produce a material that has both a high piezoelectric coefficient and good flexibility (Wu et al., 2024). By finding the right composition of materials in piezocomposites, their enhanced piezoelectric properties can advance piezoelectric biomaterial uses in tissue engineering (Wu et al., 2024). Essentially, they combine the advantages of ceramics and polymers (Wu et al., 2024). For example, the polymer polycaprolactone (PCL) is a flexible, biocompatible and biodegradable material used in tissue engineering. $BaTiO_3$ (BT) can be blended with PCL to produce a PCL/BT piezocomposite that displays piezoelectric properties and increased adhesion to cells compared to pure PCL (Wu et al., 2024). Future research is currently aiming to incorporate particles of piezoelectric ceramics into polymers used in traditional tissue engineering processes to form novel smart piezocomposites for biomedical applications (Wu et al., 2024).

3.2 Application of Piezoelectric Materials in Tissue Regeneration

Studies have shown that electrically stimulating specific tissues can promote their regeneration and repair (Wu et al., 2024). Recently, piezoelectric scaffolds have been utilized to produce electrical signals to stimulate certain cells (Wu et al., 2024). A variety of human tissue cells have been observed to possess notable piezoelectric properties and electrical activity, with prominent examples being bone and nerve tissues (Wu et al., 2024). The cellular mechanism of piezoelectricity revolves around the adhesion, migration and movement of cells within the body (Wu et al., 2024). Due to these actions, cells cause the mechanical deformation of their environment, producing a small electric field (Wu et al., 2024). These electric fields are then able to disturb ion channels on cellular membranes, altering intracellular and extracellular ion concentrations, which subsequently activates cell signalling pathways (Wu et al., 2024). Through inducing endogenous electric fields, electrically responsive tissues can therefore be repaired using piezoelectric materials.

3.2.1 Integumentary Tissue Repair

The integument, commonly known as the skin, is the largest organ of the human body. It plays a protective role by acting as a barrier against pathogens, ultraviolet radiation and the external environment in general (Nain et al., 2024). In the occurrence of a skin injury, medical practitioners will prescribe passive wound dressings that, while successful at preventing infections and hydrating the skin, do not accelerate the healing process (Nain et al., 2024). The skin's healing process is complex, consisting of four stages: hemostasis, inflammation, proliferation, and remodeling (Nain et al., 2024)—as such, there is an active interest in increasing the rate of wound healing.

Damaged skin cells generate and maintain an electric field until wound closure is completed, which is done in order to ensure healthy skin regeneration (Nain et al., 2024). Electrical stimulation via piezoelectrics can mimic these natural electric fields by applying an external electric field at the wound site (Nain et al., 2024). This in turn promotes regenerative activities by stimulating or influencing molecular pathways such as the phosphatidylinositol 3-kinase (PI3K) and phosphatase and tensin homolog (PTEN) pathways (Nain et al., 2024). Electrical stimulation (ES) from piezoelectric materials have, in recent studies, been found to impact three of the four wound healing stages, namely the inflammation, proliferative and remodeling phases. Piezoelectric ES has been found to increase the tissue oxygen and blood flow around the wound site. This clears bacteria from the wound region and decreases edema (swelling) of the wound (Nain et al., 2024). During the proliferative phase, piezoelectricity is able to accelerate wound contraction rates through increased fibroblast proliferation and migration, which are cells responsible for producing collagen and ECM (Nain et al., 2024). During the remodelling phase, due to the increase in fibroblasts, piezoelectricity enhances collagen formation which subsequently supports wound recovery (Nain et al., 2024).

For wound healing purposes, lead-free piezoceramics such as BTO, KNN, lithium sodium potassium niobate (LNKN), and zinc oxide (ZnO) have been tested (Nain et al., 2024). With small mechanical deformation, piezoceramics are able to induce electric fields which have been established to aid in integumentary tissue regeneration (Nain et al., 2024). However, piezoceramics are limited by their lack of flexibility. Due to this, piezopolymers and their composites have begun to be investigated for soft tissue regeneration because of their flexibility and biocompatibility (Nain et al., 2024). For example, the 3D-printed ZnO/PVDF/sodium alginate (ZPFSA) composite has been shown to accelerate wound healing in rodent skin wound tests (**Fig. 2**).

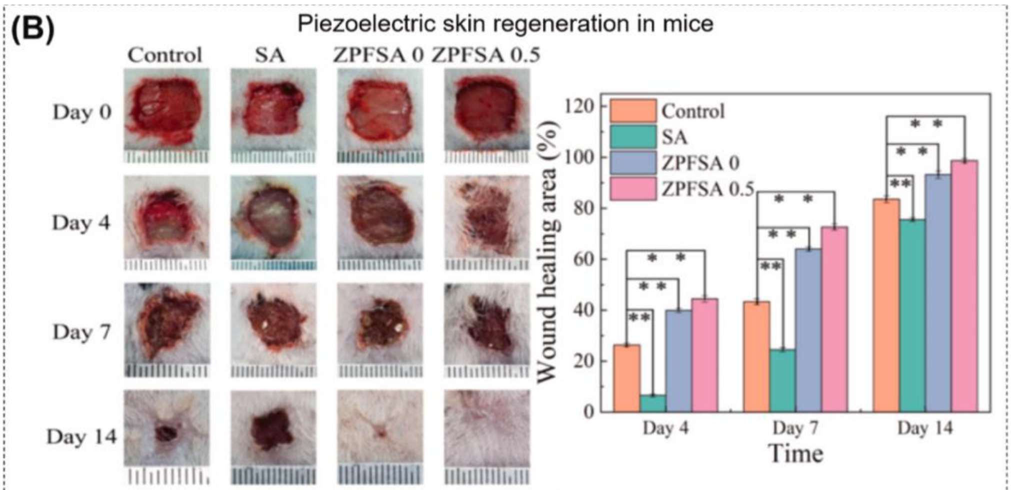

Figure 2: Wound Healing Over Time with Different Piezoelectric Scaffold Treatments (Liang et al., 2022)

3.2.2 Neural Tissue Repair

The nervous system is an important physiological system that coordinates bodily functions. Damage to the nervous system can be very debilitating to individuals, with common examples of neurological abnormalities being Alzheimer's disease and amyotrophic lateral sclerosis (ALS) (Nain et al., 2024). For these reasons, the regeneration of neural tissue has become a leading topic in research. The nervous system can be divided into two main branches, the central nervous system (CNS) and the peripheral nervous system (PNS). Most research has been centered around the PNS due to its greater nerve regeneration potential (Nain et al., 2024).

Traditional ES methods have been used to send weak electric currents across damaged tissue for the purpose of neural repair (Nain et al., 2024). The main constraint of these methods was the inconvenience created for patients, as traditional ES required the use of complex electronic setups and external electrodes (Nain et al., 2024). A non-invasive alternative was found in piezoelectric materials, which have displayed great potential in neural tissue repair due to nerve cells being naturally electrically active (Nain et al., 2024)—sending and receiving action potentials. When subjected to mechanical deformation, piezoelectrics can induce a piezopotential which activates voltage-gated ion channels on nerve cell membranes and allows its electric signals to travel down axons to promote neural repair (Nain et al., 2024).

Piezoelectric ceramics have been used as electrically active nano scaffolds for nerve repair (Nain et al., 2024). The piezopotential generated inside piezoelectrics has been observed to control Ca^{2+} ion signalling pathways, allowing extracellular Ca^{2+} ions to enter neuron cytoplasms (Nain et al., 2024). It has been found that piezoceramic treatment has resulted in the promotion of axon development, dendritic outgrowth, cell differentiation and proliferation and angiogenesis (Nain et al., 2024). PZT has been used in the production of wireless nerve scaffolds that directly attach to peripheral nerves. When the PZT-based device was tested on a rat's sciatic nerve, it was able to successfully activate motor axons and amplify postsynaptic currents, enhancing neuronal activity (Nain et al., 2024).

Piezopolymers such as poly(lactic-co-glycolic) acid (PLGA) and PLLA have been used to produce porous, flexible and biodegradable nerve conduits (Nain et al., 2024). Another polymer, namely PVDF, has been used in scaffolds due to its ability to mimic the ECM (Nain et al., 2024). PVDF triggers Schwann cell—cells that make up the myelin sheath of peripheral neurons—proliferation and attachment (Nain et al., 2024). PVDF also triggers axon remyelination, motor function repair and increased nerve conduction velocity which point to its potential as a material for nerve regeneration (Nain et al., 2024).

Another approach to neural regeneration is to instead use piezoelectric materials to stimulate neural stem cells (NSCs) into differentiating into neurons (W. Wang et al., 2025). This method displays promise in treating cases of traumatic brain injury (TBI) as it replaces lost neurons (W. Wang et al., 2025). However, NSC activity is rather slow and inefficient, meaning that these cells cannot proliferate or differentiate quickly enough to repair any significant neural damage (W. Wang et al., 2025). In order to overcome this obstacle, W. Wang et al. (2025) describes using barium titanate–reduced graphene oxide (BTO/rGO) hybrid piezoelectric nanostickers. These nanostickers function by attaching to the membranes of NSCs, generating piezopotentials when exposed to ultrasonic stimulation (W. Wang et al., 2025). The efficacy of this treatment was observed in testing done by W. Wang et al. (2025), where an increased expression of neuronal markers Tuj1 and MAP2 were seen in ultrasonically activated nanostickers on NSCs, without increased expression of neuroglial markers. Essentially, by using different markers to differentiate neurons from neuroglial cells (that function in neuron structural support), it was found that these nanostickers promoted the differentiation of NSCs into neurons rather than glial cells. This points towards the potential of piezoelectric stimulation to prioritize and accelerate neuronal differentiation, which is critical to neural regeneration.

4 MICRO-ENGINEERED PIEZOELECTRIC ARTIFICIAL MUSCLES FOR ADVANCED BIOMEDICAL APPLICATIONS

In the field of smart materials within biomedical engineering, piezoelectric materials have recently gained attention as a promising candidate for the development of artificial muscles. Their unique ability to convert electrical energy into mechanical motion mirrors the natural function of muscles, which operate through both electrical signaling and mechanical movement (Shi & Yeatman, 2021). While piezoelectric materials are more commonly recognized for their role in converting mechanical stress into electrical energy, their bidirectional capability makes them particularly valuable for innovative biomedical applications. These materials can be used to create compact, efficient actuators that benefit individuals with motor impairments, neuromuscular disorders, or limb loss (Henaux et al., 2002). When paired with piezoelectric sensors, they enable the creation of smart structures that closely mimic the form and function of natural muscles (Gupta et al., 2010). To ensure optimal performance, careful consideration must be given to the placement and configuration of both the sensors and actuators within the artificial muscle (Gupta et al., 2010). In particular, tailoring these configurations to different structural forms such as within beams is essential to maximizing the effectiveness of this emerging technology.

4.1 General Key Components of Artificial Piezoelectric Muscles

Artificial muscles are also known as piezoelectric actuators within this application as they can contract or expand when triggered by stimuli such as electric or magnetic fields, thermal energy, or electrochemical reactions (Mirvakili & Hunter, 2017). These muscles mimic biological ones and represent an evolution in how force and movement are generated, replacing the reliance on human and animal muscles. As shown in Table 1, different microsystems perform different functions ranging from response, frequency, power, etc. Therefore, a "preferred" artificial muscle depends on what the microsystem needs to do (Shi & Yeatman, 2021). For example, within microsurgery applications, a very precise and controllable artificial muscle would be preferred, therefore piezoelectric materials would be chosen to apply these characteristics (Shi & Yeatman, 2021).

To gain a further understanding of energy delivery and conversion in a microsystem utilizing piezoelectric actuator mechanisms, it is essential to first analyse the individual components of its basic structure. This insight is crucial for evaluating how piezoelectric actuators contribute to artificial muscle design, as well as how the configuration of both piezoelectric sensors and actuators plays a vital role in ensuring effective functionality in terms of its function.

The schematic presented in **Figure 3** is of a basic design of a microsystem smart structure. Outlined within the figure are multiple crucial components beginning with the piezoelectric sensor. The piezoelectric sensor provides a crucial function as when the artificial muscle moves or experiences external forces (mechanical stress), an electrical signal is generated due to a direct piezoelectric effect (Shi & Yeatman, 2021). This signal is then sent to the processor, providing real-time feedback as the piezoelectric sensors are embedded in or around the artificial muscle (Gupta et al., 2010). This feedback signal is crucial for self regulation and precision control (such as microsurgery) of the muscle. The processor is known as the control unit and acts as the brain of the system and as it receives feedback from the sensor, it uses it to determine the state of the beam such as how much it is bending or if an external force is being applied (Gupta et al., 2010). It then calculates how much actuation is needed to correct or maintain specific motion or force and responds to this sensory input by sending the information through control signals to the amplifier. This is to modify the desired current or voltage needed to adjust the muscles movement accordingly and moves towards the piezoelectric actuator (Gupta et al., 2010).

The piezoelectric actuator allows for physical movement to occur in response to the electrical signals being transmitted (Gupta et al., 2010). Specifically in piezoelectric artificial muscles, the actuator typically consists of layered piezoelectric materials that deform when an electric field is applied. Based on the configuration of the sensor and actuator, the actuator can either perform axial, lateral, or torsional motion (Gupta et al., 2010). The piezoelectric actuator is attached directly to the cantilevered beam which serves as the structural framework of the artificial muscle system. The beam is embedded/coated with strong specified piezoelectric materials such as PZT (lead zirconate titanate) or PVDF (polyvinylidene fluoride) (Gupta et al., 2010). When voltage is applied to these materials a mechanical deformation is generated and the beam then bends or flexes. However, when force is applied to these materials an electrical charge is generated. The beam not only moves but also begins to “feel” its own deformation, contributing to the feedback loop (Gupta et al., 2010). This control-loop control provides precision and adaptability allowing the muscle to respond dynamically just like how natural muscle responds to sensory input.

Table 1: Different microsystem applications matched to types of artificial muscles and mechanisms based on their requirements (Shi & Yeatman, 2021)

Microsystem Applications	Critical Requirements	Types of Artificial Muscle Mechanisms
Microsurgery	Fine motion, controlled force, quick response, safe	Piezoelectric, Magnetic, pneumatic
Micro flying robots	High frequency, high power/mass ratio, untethered	Piezoelectric, DE
Micropumps	Large stroke, quick response, waterproof	Piezoelectric, pneumatic, IPMC
Artificial insect exoskeleton	High power, large stroke, quick response	Piezoelectric, IPMC

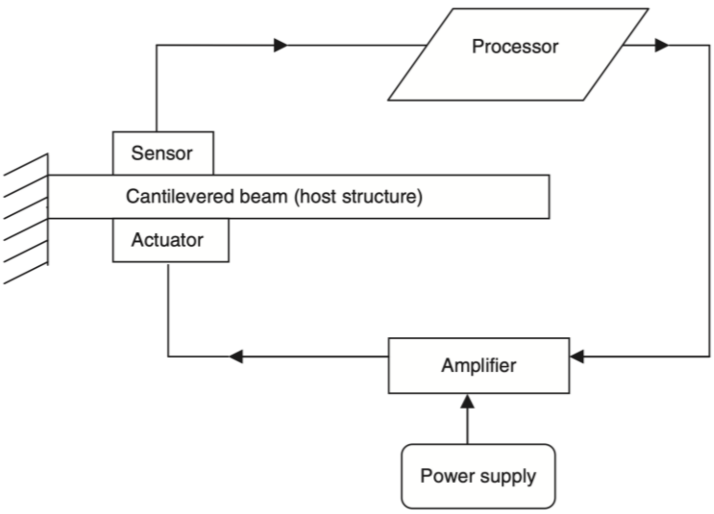

Figure 3: Schematic of a Simple Smart Microsystem (Gupta et al., 2010)

4.1.1 Chosen Piezoelectric Materials: PZT and PVDF

The cantilevered beam of the smart structure represents the focal point of the framework of the artificial muscle system where it could represent a joint, robotic finger, or even mimic soft tissue depending on the application. Due to the importance of this component, it is vital to use the appropriate type of piezoelectric material in order to ensure that functional and responsive motion is achieved. PZT (lead zirconate titanate) and PVDF (polyvinylidene fluoride) present to be the most promising choice due to their electromechanical properties (Shi & Yeatman, 2021). PZT is a commonly used piezoceramic which offers high electromechanical coupling and efficiency that produces up to 0.2% strain (Mirvakili & Hunter, 2017). Due to its characteristic low strain percentage, it is ideal for precise, and high force actuation in semi rigid or rigid beam applications (Mirvakili & Hunter, 2017). PVDF presents an option of an organic piezoelectric polymer that is softer, lightweight, and more flexible than PZT (Shi & Yeatman, 2021). These distinctive features make it highly suitable for low impedance, soft bodied systems that are designed to interact with biological tissues in safe and compliant ways. PVDF has already demonstrated potential in successful cantilever actuators applications and insect-scale soft robots which present the materials capacity for significant deformation under low voltage input (Shi & Yeatman, 2021). When layered onto or embedded into the cantilever beam these materials allow for adaptive stiffness, controlled deformation, and high resolution motion which provides the groundwork for effective artificial muscle application through biomedical and robotics applications (Shi & Yeatman, 2021).

5 APPLICATIONS OF PIEZOELECTRIC MATERIALS IN BIOMEDICAL IMPLANTS

Piezoelectricity can be used in a variety of applications in the human body, including different body implants like cochlear implants and cardiac pacemakers. In these upcoming two sections, the discussion is about how piezoelectric materials and filaments can be used to harvest energy for charging pacemakers, without the need of lithium batteries and how filaments of different type of piezoelectric materials can be set in the cochlear duct to improve hearing problems. Limitations of this technology in cardiac pacemakers and cochlear implants are also discussed showing how far this technology is progressing and how it is very promising for lots of developments in the future.

5.1 Cardiac Pacemakers

In cardiac pacemaker applications, an instantaneous piezoelectric nanogenerator (i-PENG) is designed to enhance the conversion of mechanical energy to electrical energy for powering the pacemaker. The traditional nanogenerators (NGs) struggled with low energy conversion, but i-PENG significantly converts the wave-like output of a regular PENG into output spikes with ~7 times higher amplitude (D. Wang et al, 2025). Additionally integrated with a rectifier and micro capacitor, the whole system acts as an electrical regulator and allows the pacemaker to have a faster charging rate. Another issue that occurs with pacemakers powered with regular lithium batteries is that it can cause infections and lead to surgical replacements (Kabir et al., 2022). Therefore researchers have been trying to discover different ways to harvest the biomechanical energy from the blood flow, heart beats, and chest motion as a sustainable power supply for the pacemaker. i-PENG incorporates additional contact electrodes that help with transforming wave-like outputs into sharp spikes with over four times higher amplitude for this purpose (Fig. 4).

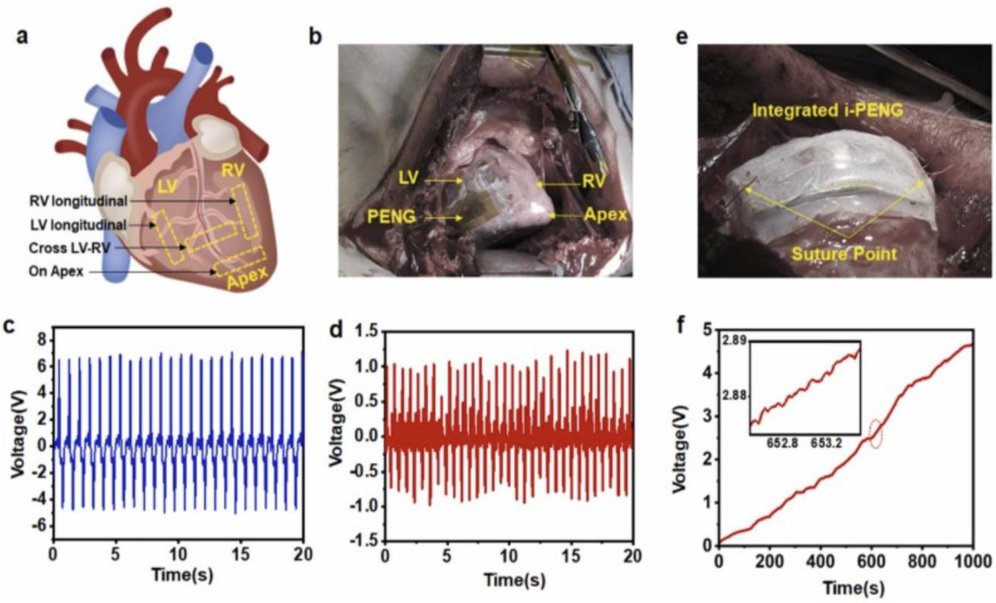

Figure 4: The voltage captured for harvesting energy for the pacemaker implant on the heart in addition to showing the areas of where the piezoelectric layer is implanted. Reused with consent from (D. Wang et al, 2025).

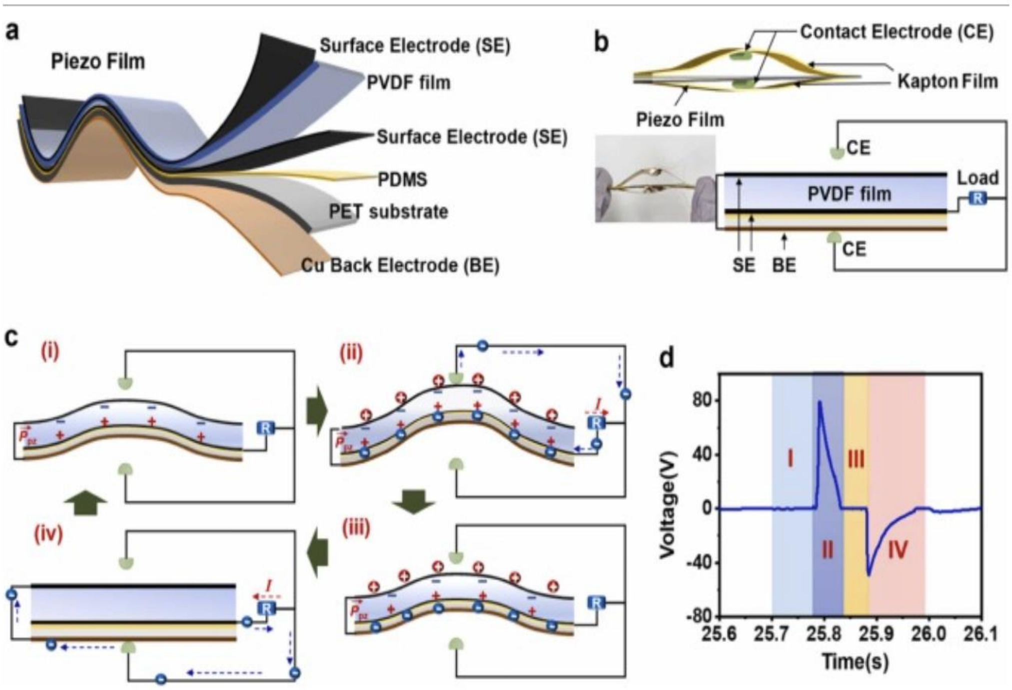

Figure 5: The layers involved in the piezoelectric pacemakers showing the PVDF film layer and how it would detect the electrical signals. Reused with consent from (D. Wang et al, 2025).

Piezoelectric materials, particularly polyvinylidene fluoride (PVDF) and ceramics like barium titanate ($BaTiO_3$), are being explored to improve the performance of these generators. PVDF is a very flexible piezoelectric material that can be implanted within the human body due to its biocompatibility and good piezoelectric properties. In addition, it can be combined with barium titanate nanoparticles which can enhance the overall performance and efficiency of the pacemaker. This is conducted by the piezoelectric patch which harvests the internal energy from heart beats and internal motion of cardiac muscles. In using piezoelectric energy harvesters (PEHs) in pacemakers, the need for replacement surgeries may be reduced due to energy harvesting from heart movements (Hu & Behdinan, 2023).

While nanogenerators such as the i-PENG are designed to improve energy output rates, a challenge encountered with these PEHs is that they often use animal models to evaluate performance (Hu & Behdinan, 2023). For multiple designs or prototypes, this can prove to be both timely and costly and in addition, may not be scalable to human use due to anatomical differences between test species and humans (Hu & Behdinan, 2023). To address these issues, Hu & Behdinan (2023) describes fluoroscopy imaging as a method to record the motion of a pacemaker lead wire (PLW) in vivo to later be used for simulation. Using these models, researchers may be able to create simulations to determine the energy output of PEHs under more accurate physiological conditions (Hu & Behdinan, 2023). From their results, one of their PEH models has the potential to increase a pacemaker's battery life by 0.75-1 years based on its power output (Hu & Behdinan, 2023). Thus, PEH designs have the potential to decrease dependency on animal models, and lengthen the operational lifetime of pacemakers, in addition to creating medical devices that can sustain themselves without battery power (Hu & Behdinan, 2023). Figure 5 visually demonstrates the working principle of PVDF-based piezoelectric pacemakers, where deformation of the layered film produces alternating voltage signals corresponding to each heartbeat (D. Wang et al, 2025). This representation complements Hu and Behdinan's (2023) findings by illustrating how internal cardiac motions can be harnessed as a renewable energy source within implantable devices.

5.2 Cochlear Implants

Hearing loss is projected to affect over 2.5 billion people by 2050 with sensorineural hearing loss (SNHL) (Mokhtari et al., 2025). This is due to the inability of hair cells to regenerate in the internal ear, causing issues with neurotransmitter release and reception by the hearing receptors in the cochlear duct (Mokhtari et al., 2025). The cochlea's basilar membrane plays a critical role in detecting sound vibrations through the movement of those hair cells and converting them into electrical signals for auditory processing (Mokhtari et al., 2025). Since piezoelectric materials can generate their own electrical signals by converting mechanical energy or deformation, they hold promise in the use of this innovative technology in the biomaterial field of cochlear implants. Researchers explored two types of piezoelectric materials that can be used in the cochlear duct, namely polyvinylidene fluoride (PVDF) and lead zirconate titanate (PZT), to mimic the function of natural hair cells (Mokhtari et al., 2025). While both materials are very good candidates for the use in the cochlear duct, it is preferred to use PVDF more than PZT, because it is more biocompatible with the internal ear and epithelial tissues, as it doesn't impose toxic risks like PZT-based sensors do (Mokhtari et al., 2025). This is due to PZT-based sensors being too brittle and posing biocompatibility concerns due to lead content (Mokhtari et al., 2025). The process depicted in Figure 6 demonstrates how PVDF-based piezocomposite filaments could be integrated into cochlear implants to translate mechanical vibrations into electrical impulses, aligning with Mokhtari et al.'s (2025) findings on enhanced piezoelectric and acoustic-to-electric conversion performance.

The development of PVDF-based nanocomposite fibers incorporating barium titanate (BT) and reduced graphene oxide (rGO) aim to enhance piezoelectric properties for sensing applications (Mokhtari et al., 2025). BT, with its high piezoelectric coefficient and biocompatibility, improves β-phase formation in PVDF, while rGO enhances conductivity and crystallinity (Mokhtari et al., 2025). Scanning electron microscopy and X-ray diffraction analysis showed uniform dispersion of nanofillers and increased β-phase content, which is crucial for improved piezoelectric performance. Mechanical testing demonstrated enhanced tensile strength and Young's modulus in PVDF/rGO composites, while thermal and conductivity analysis confirmed increased crystallinity and electrical properties (Mokhtari et al., 2025). Although PVDF looks promising in the cochlear implant field and seems that it can potentially develop the acoustoelectric performance of the filaments by converting sound waves into electrical signals, its piezoelectric response and frequency discrimination remain suboptimal (Mokhtari et al., 2025). This was observed through a testing procedure by Mokhtari et al. across frequencies ranging from 50 to 1000 Hz in Figure 7, where the peak voltage output occurred at 250 Hz, with PVDF/rGO filaments generating the highest voltage (7.5 mV) (Mokhtari et al., 2025). This surpassed previous artificial cochlear sensors, indicating that there is high potential in using piezoelectric materials. These results enable the cochlear transducer to function as a self-powered implant that does not require external power sources to function (Mokhtari et al., 2025).

Moving away from creating cochlear implants from piezoelectric materials, another concern in otology is whether medical devices can be safely used without interfering with existing cochlear implants during medical procedures. This is a concern because external devices have the potential to induce a current in the electronics of the implant, leading to excessive heating and failure (Kulekci, 2023). Thus, there exists a desire for an external device that does not produce electric current in the presence of cochlear implants. In a novel case, Kulekci (2023) describes the use of piezosurgical tools for a septorhinoplasty on a 22-year old patient with cochlear implants. Since piezosurgical tools utilize ultrasonic waves to cut bones, Kulekci (2023) theorized that there would be no complications. This assumption was confirmed when the procedure was completed and the patient felt no changes to their hearing ability both immediately and one month post-operation (Kulekci, 2023). This is the first recorded case in which piezosurgical instruments were used to operate on a patient with cochlear implants without complication (Kulekci, 2023). This case provides initial evidence that piezosurgery is a safe and viable alternative to standard surgery and instrumentation for performing on cochlear implant users. As this is only a single case, a definite conclusion cannot be made on piezosurgical safety. However, Kulekci (2023) has paved the way for further investigation into using ultrasonic, piezoelectric instruments in surgery to mitigate the risk of damaging cochlear implants.

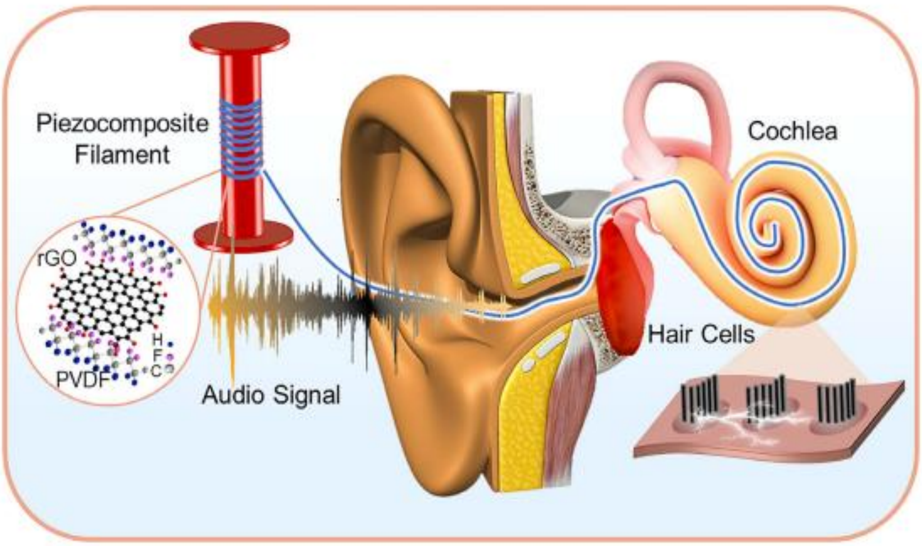

Figure 6: The piezoelectric filament used in cochlear implant through the cochlear duct to receive electrical signals and improve hearing. Reused under CC BY 4.0 license (Mokhtari et al., 2025).

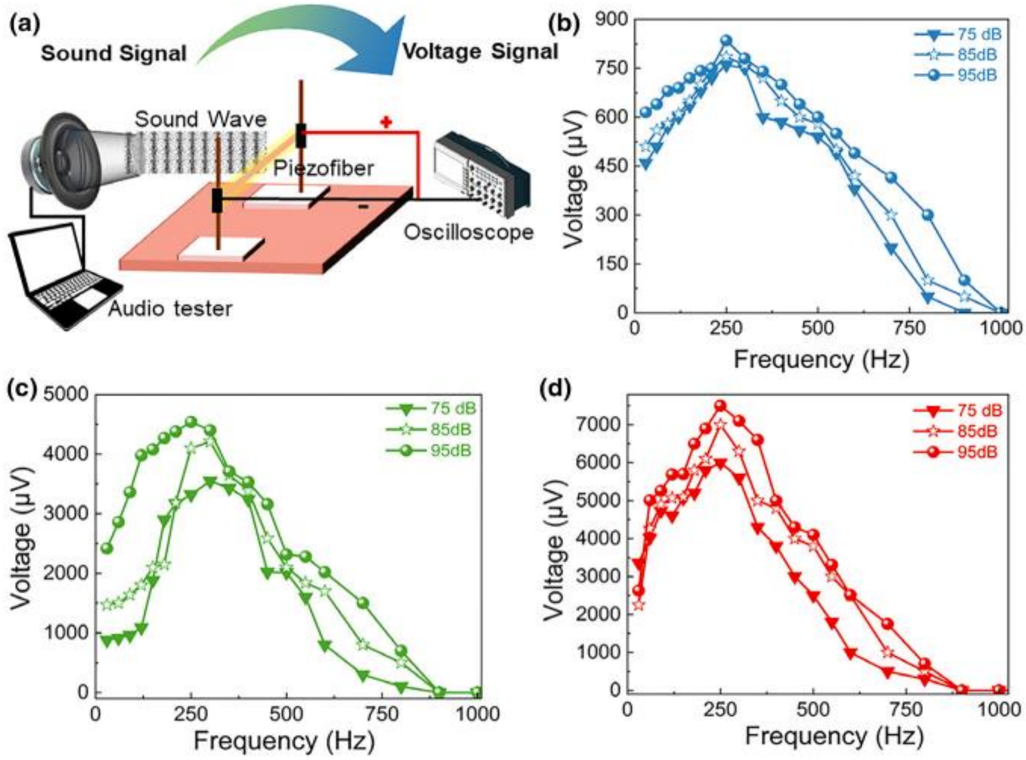

Figure 7: a) A schematic diagram showing the setup for exposing filaments to sound waves as the voltage outputs depend on sound frequency at the three different sound pressure levels for b) PVDF, c) PVDF/BT , and d) PVDF/rGO filaments. Reused under CC BY 4.0 license (Mokhtari et al., 2025).

6 PIEZOELECTRIC BIOMATERIALS IN BONE TISSUE REGENERATION

Traditional medical approaches to bone repair through surgery and medication often fail to fully restore the structural and functional integrity of damaged tissues (Panda et al., 2022). Recent advances in biomaterials science have revealed the remarkable potential of piezoelectric materials–substances capable of generating electrical charges in response to mechanical stress–as innovative solutions for tissue regeneration (Yang et al., 2022). This electromechanical property holds particular significance for bone tissue, which naturally exhibits piezoelectric behaviour due to its collagenous matrix composition (Khare et al., 2020).

The human body's tissues function as sophisticated electrochemical systems where electrical signals play vital roles in cellular communication and tissue maintenance (Panda et al., 2022). Piezoelectric biomaterials capitalize on this natural phenomenon by providing endogenous electrical stimulation that enhances bone healing without requiring external power sources (Yang et al., 2022). This capability positions piezoelectric materials as a revolutionary approach in regenerative medicine, offering solutions that bridge the gap between structural support and biological activity (Panda et al., 2022).

6.1.1 Inorganic Piezoelectric Materials for Bone Regeneration

Piezoelectric crystals such as quartz (SiO_2) and lithium tantalate ($LiTaO_3$) exhibit consistent piezoelectric effects due to their crystallographic arrangements (Panda et al., 2022). These materials prove particularly valuable for sensor applications, where stability and precision are paramount, though their clinical use in bone regeneration has been limited by processing challenges and difficulties in biological integration (Yang et al., 2022).

Polycrystalline ceramics including barium titanate ($BaTiO_3$) and lead zirconate titanate (PZT) demonstrate significantly higher piezoelectric coefficients compared to single crystals, owing to their domain structures (Panda et al., 2022). Barium titanate has emerged as a frontrunner, due to its combination of high piezoelectric coefficient (d_{33} $\approx$ 190 pC/N), excellent biocompatibility, and ability to promote hydroxyapatite nucleation (Yang et al., 2022). Recent studies have shown that barium titanate nanoparticles can enhance osteogenesis through both piezoelectric stimulation and direct biochemical interactions (Panda et al., 2022). However, concerns regarding the cytotoxicity of certain ceramic components, particularly the lead content in PZT, have driven research toward developing lead-free alternatives, such as potassium sodium niobate (KNN) as well as lithium sodium potassium niobate (LNKN) (Panda et al., 2022).

6.1.2 Organic Piezoelectric Materials for Bone Regeneration

Organic piezoelectric materials, primarily polymers, offer distinct advantages for bone regeneration applications due to their flexibility and biocompatibility (Panda et al., 2022). Among synthetic piezoelectric polymers, polyvinylidene fluoride (PVDF) and its copolymer PVDF-TrFE have demonstrated promise, exhibiting high piezoelectric coefficients (d_{33} up to -30 pC/N) and the ability to be processed into various forms–including films, fibres, and porous scaffolds which enhance osteoblast proliferation and differentiation (Yang et al., 2022). Poly-L-lactic acid (PLLA), an FDA-approved biodegradable polymer with a piezoelectric coefficient of $d_{14} \approx -10$ pC/N, has shown value for temporary implants designed to gradually transfer the load to healing bone (Khare et al., 2020).

Natural piezoelectric polymers include several biological macromolecules with piezoelectric properties that make them suitable for regenerative applications (Yang et al., 2022). Collagen, as the primary organic component of bone matrix, demonstrates piezoelectric behaviour from its triple-helix structure allowing it to generate electrical potentials under mechanical stress which plays a crucial role in bone remodelling (Panda et al., 2022). Chitosan, derived from the organic material chitin, has emerged as another promising alternative for bone regeneration scaffolds due to its non-centrosymmetric crystal structure, biodegradability, and osteoconductive properties (Zhao et al., 2022).

6.1.3 Piezoelectric Composites for Bone Regeneration

These hybrid materials aim to achieve enhanced piezoelectric responses from ceramic components, while maintaining improved mechanical compliance from polymer matrices along with tailored degradation profiles for the specific application (Yang et al., 2022). Notable examples of this include PVDF-$BaTiO_3$ composites that have demonstrated output voltages up to 5 V under physiological loading conditions (Zhao et al., 2022), PLLA-$BaTiO_3$ scaffolds that combine biodegradability with sustained electrical stimulation (Khare et al., 2020), and collagen-HA-$BaTiO_3$ systems designed to mimic both compositional and electromechanical properties of natural bone (Chen et al., 2021).

6.2 Mechanisms of Piezoelectric Bone Regeneration

The therapeutic effects of piezoelectric materials in bone regeneration operate through multiple interconnected mechanisms that span molecular to tissue-level responses (Khare et al., 2020). At the cellular level, piezoelectric potentials (typically 50-200 mV/mm) have been shown to enhance osteoblast proliferation and differentiation while upregulating key osteogenic markers–including RUNX2, osteocalcin, and alkaline phosphatase (Yang et al., 2022). Simultaneously, negative surface charges on piezoelectric materials suppress osteoclast activity, by inhibiting RANKL signalling pathways whilst reducing tartrate-resistant acid phosphatase activity (Zhao et al., 2022). This creates a balanced bone remodelling environment.

Molecular signalling pathways activated by piezoelectric stimulation include the Wnt/β-catenin pathway, where electrical stimulation promotes Wnt ligand binding to LRP5/6 receptors, leading to β-catenin stabilization and enhanced expression of osteogenic genes (Chen et al., 2021). The BMP/Smad pathway also responds to piezoelectric materials through increased secretion of bone morphogenetic proteins and activation of Smad1/5 phosphorylation (Yang et al., 2022), synergizing with mechanical stimulation to promote osteogenesis. Furthermore, piezoelectric potentials regulate voltage-gated calcium channels to increase intracellular Ca^{2+} concentration and activate calmodulin-dependent pathways that promote cell proliferation (Khare et al., 2020).

Looking at the macroscopic level, piezoelectric bone regeneration scaffolds demonstrate enhanced extracellular matrix deposition, improved collagen alignment and mineralization, as well as accelerated defect closure in animal models (Cen et al., 2021). These tissue-level effects combine to create an optimal environment for bone regeneration that mimics the body's natural healing processes, while providing additional therapeutic stimulation (Zhao et al., 2022).

6.3 Clinical Applications and Future Directions

Piezoelectric materials are being utilized in several clinical applications for bone repair (Yang et al., 2022), including orthopedic implants such as piezoelectric fixation plates and screws, which provide mechanical stabilization while delivering localized electrical stimulation and gradually resorbing as the bone heals (Khare et al., 2020). In bone graft substitutes, 3D-printed piezoelectric scaffolds are being developed for critical-sized defects (Zhao et al., 2022), which feature customizable pore architectures to facilitate vascular ingrowth and bioactive coatings to enhance osseointegration (Chen et al., 2021). Dental applications have also emerged, which include piezoelectric membranes for guided bone regeneration, implant coatings to enhance osseointegration, and specialized devices for periodontal repair (Yang et al., 2022).

6.3.1 Challenges and Limitations

Despite significant research progress, challenges remain in the field of piezoelectric bone regeneration (Wu et al., 2024). Material limitations include the need to balance piezoelectric performance with biodegradability, whilst ensuring long-term stability of electrical output and addressing potential cytotoxicity of certain components (Kamel, 2022). Clinical translation barriers involve standardizing electrical stimulation parameters; scaling up from small animal models to human applications and navigating regulatory approval pathways for piezoelectric devices (Yang et al., 2022).

6.3.2 Prospective Research Areas

Emerging trends in piezoelectric bone regeneration focus on developing smart implant systems capable of self-regulation based on healing progress (Zhao et al., 2022), integrating sensors for real-time monitoring (Chen et al., 2021), and creating closed-loop systems that combine both electrical and biochemical cues (Khare et al., 2020). Advanced manufacturing techniques, such as 4D-printed scaffolds with dynamic piezoelectric responses and micro/nano-patterning to create optimal electrochemical microenvironments represent promising avenues for innovation (Yang et al., 2022). Biomimetic approaches that employ hierarchical designs mimicking natural bone architecture, multi-material systems replicating bone's anisotropic properties, and bioinspired self-assembly strategies are also gaining traction in the field (Wu et al., 2024).

7 FUTURE RESEARCH

As the application of piezoelectric materials for the purpose of tissue engineering stands today, research is still in its early stages (Wu et al., 2024). The development of future piezoelectric biomaterials will need to consider various factors, which boils down to optimizing the choice of materials.

There are various different tissues in the body, each with different structures and mechanical properties. As such, a challenge in the future of biomedical piezoelectric applications is to first discover the right material or amalgam of piezoceramics and piezopolymers to achieve appropriate mechanical properties, biocompatibility, and optimal piezoelectric efficiency (Nain et al., 2024). For example, to regenerate bone tissue, piezoelectric materials that mimic bone properties are required. Thus, the development of piezoelectric materials that imitate natural tissue structures and functions, such as that of the skin, nerves, heart and bone are a main topic of future research (Wu et al., 2024). While previous studies have primarily focused on the electromechanical performance of these materials in isolation, this review emphasizes the importance of tailoring them to specific tissue contexts which is an area where comparative studies remain limited and underexplored.

An additional challenge for future research is minimizing toxicity and balancing biocompatibility with mechanical properties. Many materials, such as the piezoceramic PZT, have very high piezoelectric coefficients but are composed of toxic materials, namely lead (Pb) in PZT's case. Lead-free piezoceramic alternatives such as KNN have been considered (Nain et al., 2024). These materials also have relatively high piezoelectric coefficients but due to their non-biodegradability and mechanical incompatibility with tissues, their use is minimal (Nain et al., 2024). In order to address these issues, future research not only focuses on mechanical compatibility with tissues but biological compatibility as well, in the form of biodegradable and non-toxic materials.

By bringing together material classification, biological response, and device-level application analysis, this review contributes to a more integrated understanding of how piezoelectric materials can be optimized for the use of biomedical devices. For future applications, interdisciplinary collaboration will be essential to create next-generation piezoelectric biomaterials that are functional, safe, and adaptable to clinical environments. The path ahead requires innovation not only in material science but also in translational design strategies to ensure piezoelectric materials reach their full potential in healthcare.

CONCLUSIONS

1. Piezoelectric materials convert mechanical energy into electrical energy due to their non-centrosymmetric properties making them suitable for biomedical applications.
2. The electrical signals generated by piezoelectric materials can stimulate wound healing, support artificial muscle function, and neural and bone regeneration making them promise for tissue engineering and regenerative medicine.
3. This review covered different types of piezoelectric materials, particularly biocompatible piezocomposites like PVDF and PZT, which have shown strong potential in biomedical applications.
4. Key applications include tissue regeneration, artificial muscles, biomedical implants, and bone tissue regeneration, with future developments expected to further enhance their performance and versatility.
5. Material selection is critical as biocompatibility, biodegradability, and mechanical/electrical properties must be carefully balanced for safe and effective integration into the human body.
6. While piezoelectric technologies show great promise, challenges such as biotoxicity, material performance, and complex fabrication processes remain.
7. Continued research is essential to overcome these limitations and unlock the full potential of piezoelectric materials in future biomedical and healthcare solutions.

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